Roundtable Overview, Structure, and Desired Outcome

Isik Kizilyalli
Program Director, ARPA-E

Executive Summary

Opportunity

- EGS is a ***massive technical opportunity*** (190,000 Quads extractable)
- EGS utilizes ***US natural resource advantages*** (geology)
- EGS leverages ***US human capital advantages*** (oil & gas expertise in drilling, well operation, etc.)

Challenges

- Capital-intensive, high-risk
- Chicken and egg problem for high temperature EGS
- Surveying has improved, but development has lagged

ARPA-E Vision: spark "unconventional" revolution in EGS

- Support key technologies in reservoir design and downhole tools
- Relax geographic constraints on geothermal energy
- Leverage new generation of geothermal and oil & gas talent

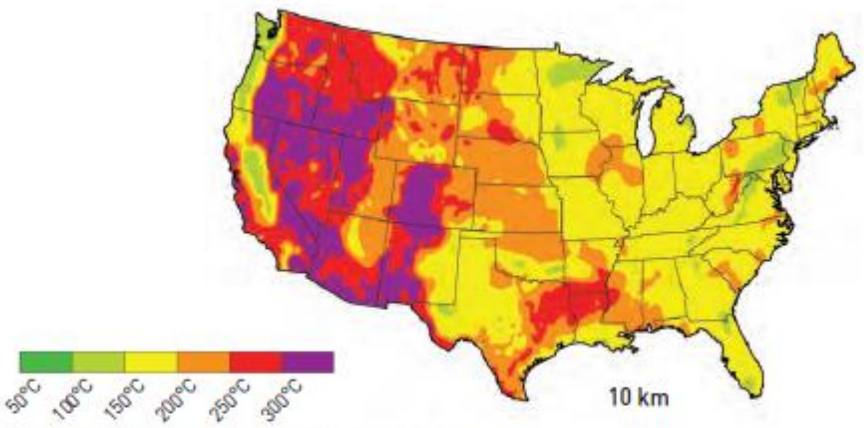


Figure 1.5 Temperatures at a depth of 10 km.

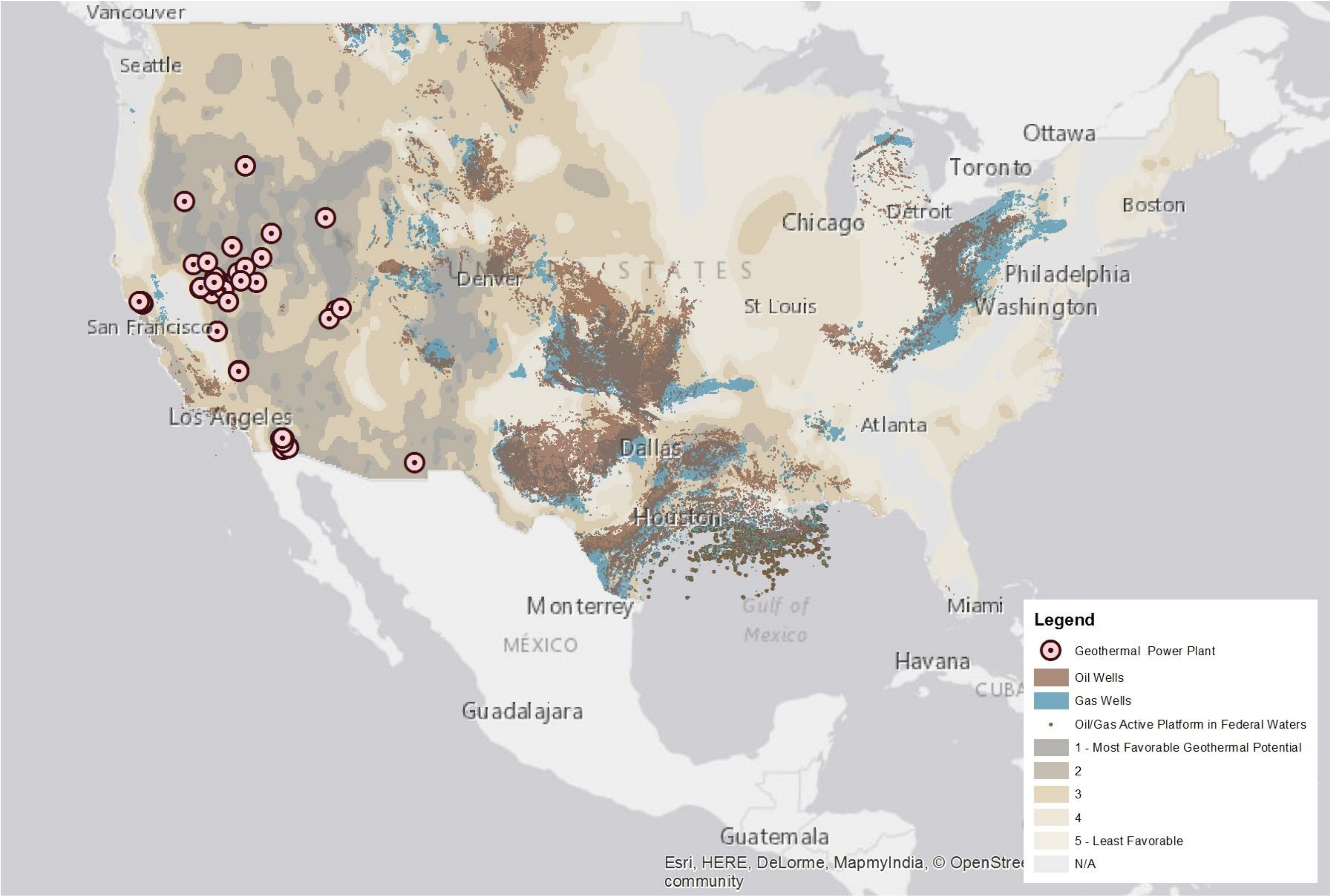
Purpose of this roundtable

- ARPA-E's mission is to overcome long-term and high-risk technological barriers in the development of energy technologies to ensure the US' technological lead and energy security:
  - Reducing imports
  - Improving energy efficiency
  - Reducing emissions
- *"If it works, will it matter?"*

- Today we will:
  - Test the hypothesis that a targeted set of investments in the right tools for enhanced geothermal systems will dramatically lower costs/risks and lead to widespread viability
  - Collect ideas from the geothermal and adjacent communities

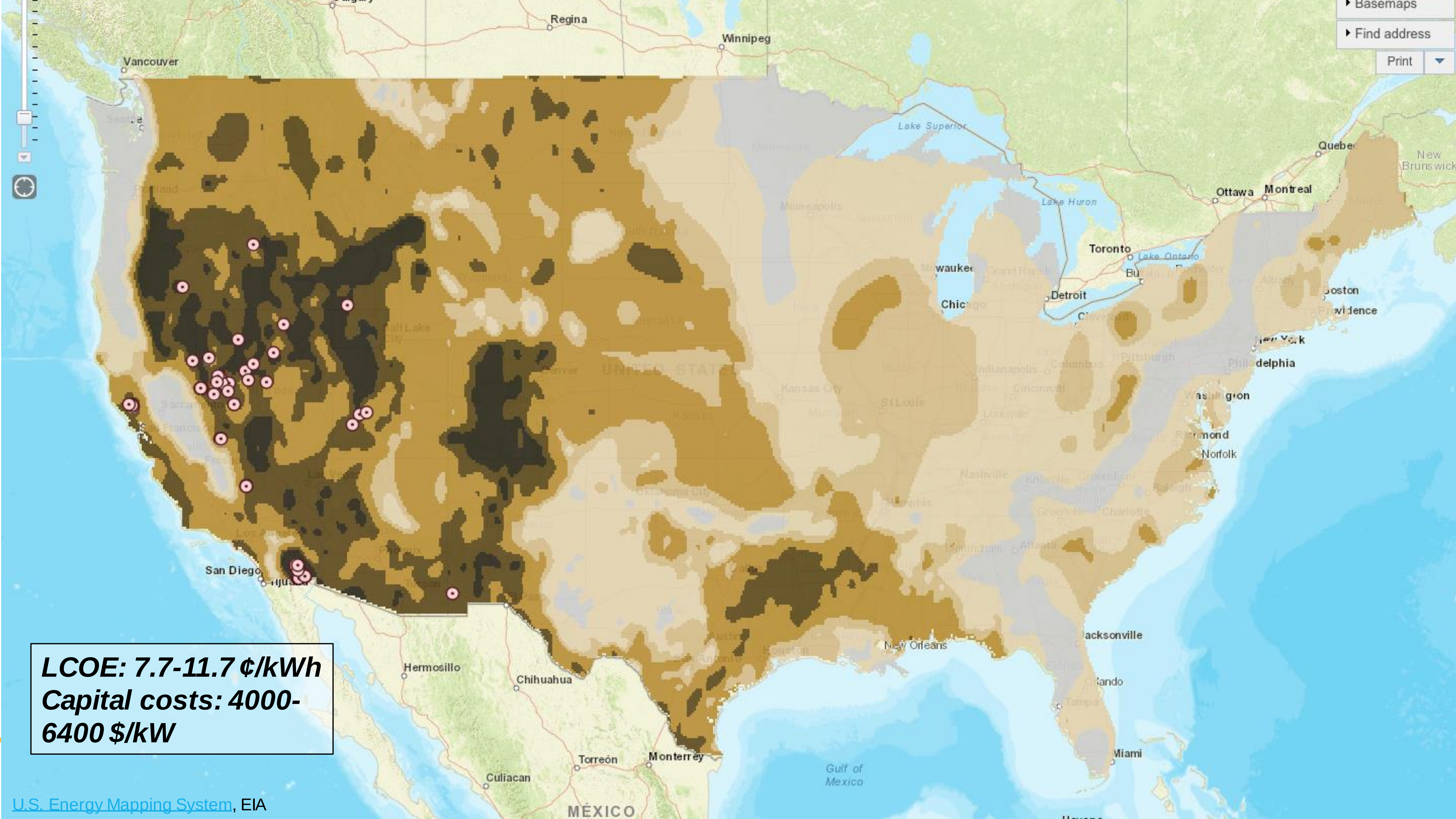
- After today:
  - A present or future ARPA-E Program Director may pitch a program in this area

Why EGS: US "proved" reserves



Resource	Supply
Oil	35B bbl proved, 200 EJ
Gas	341 TCF proved, 340 EJ
Coal	254 B ton recoverable, 5800 EJ
Uranium	45MM lb @$30/lb; 362MM lb @ $100/ton, 65 EJ
Geothermal	***200,000 EJ extractable***

U.S. Energy Mapping System, EIA
The Future of Geothermal Energy, INL, 2006
Jack Lewnard, Frontiers of Subsurface Energy Roundtable, 2018.



LCOE: 7.7-11.7 ¢/kWh
Capital costs: 4000-6400 $/kW

[U.S. Energy Mapping System](), EIA

The real prize is deeper underground

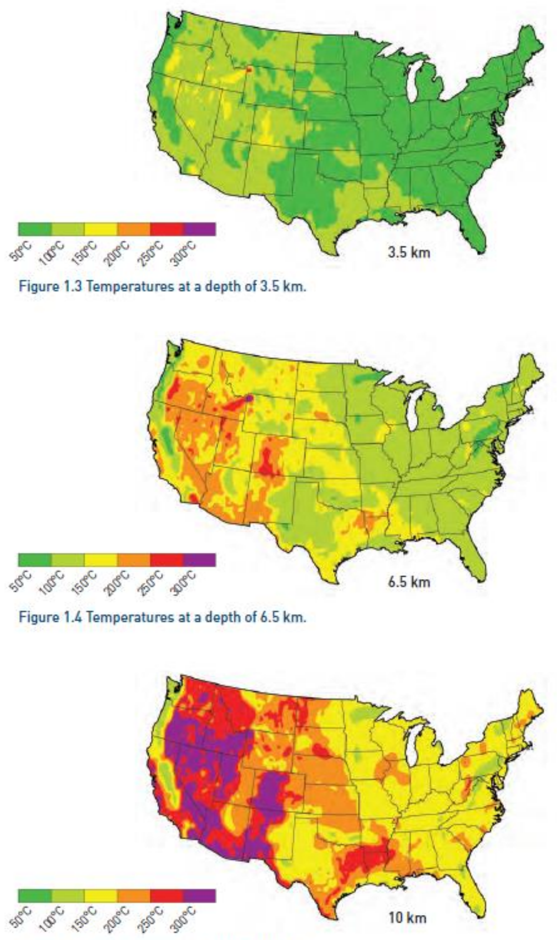


Figure 1.3 Temperatures at a depth of 3.5 km.

Figure 1.4 Temperatures at a depth of 6.5 km.

Figure 1.5 Temperatures at a depth of 10 km.

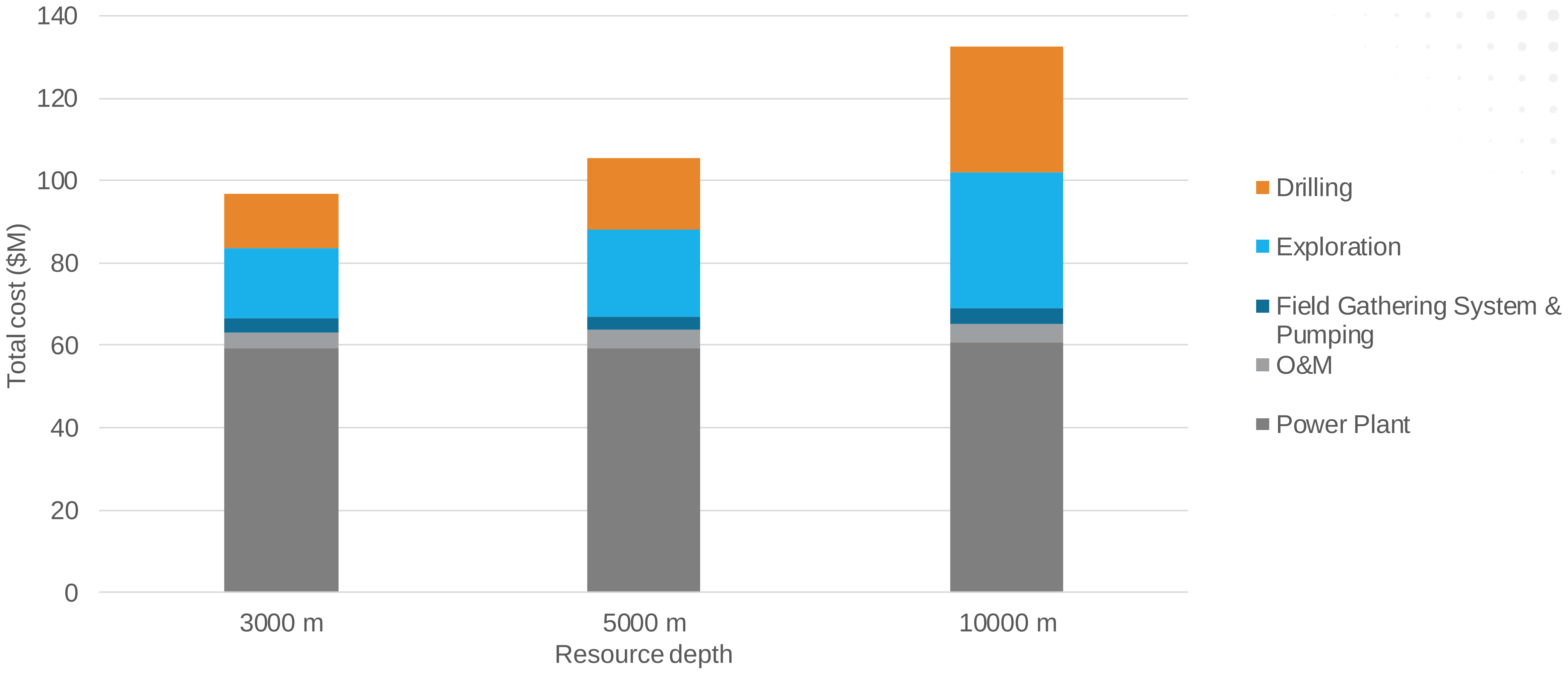
Resource		Resource Potential Capacity	
		Capacity (GW_e)	Source(s) and Description
Hydrothermal	Identified Hydrothermal Sites	6.39	USGS 2008 Geothermal Resource Assessment[1] - Identified hydrothermal sites - Sites ≥110 °C included - Currently installed capacity excluded
	Undiscovered Hydrothermal	30.03	USGS 2008 Geothermal Resource Assessment[1]
Enhanced Geothermal Systems (EGS)	Near-Hydrothermal Field EGS	7.03	Assumptions based on USGS 2008 assessment[1] - Regions near identified hydrothermal sites - Sites ≥110 °C included - Difference between mean and 95th%ile hydrothermal resource estimate
	Deep EGS	15,908	NREL 2006 Assessment[2], MIT Report[3], SMU Data[4] - Based on volume method of thermal energy in rock 3-10 km depth and ≥150 °C - Does not consider economic or technical feasibility

1 (Williams, Reed et al., 2008a)
2 (Petty and Porro, 2007)
3 (Tester et al., 2006)
4 (Richards, 2009)

The Future of Geothermal Energy, INL, 2006

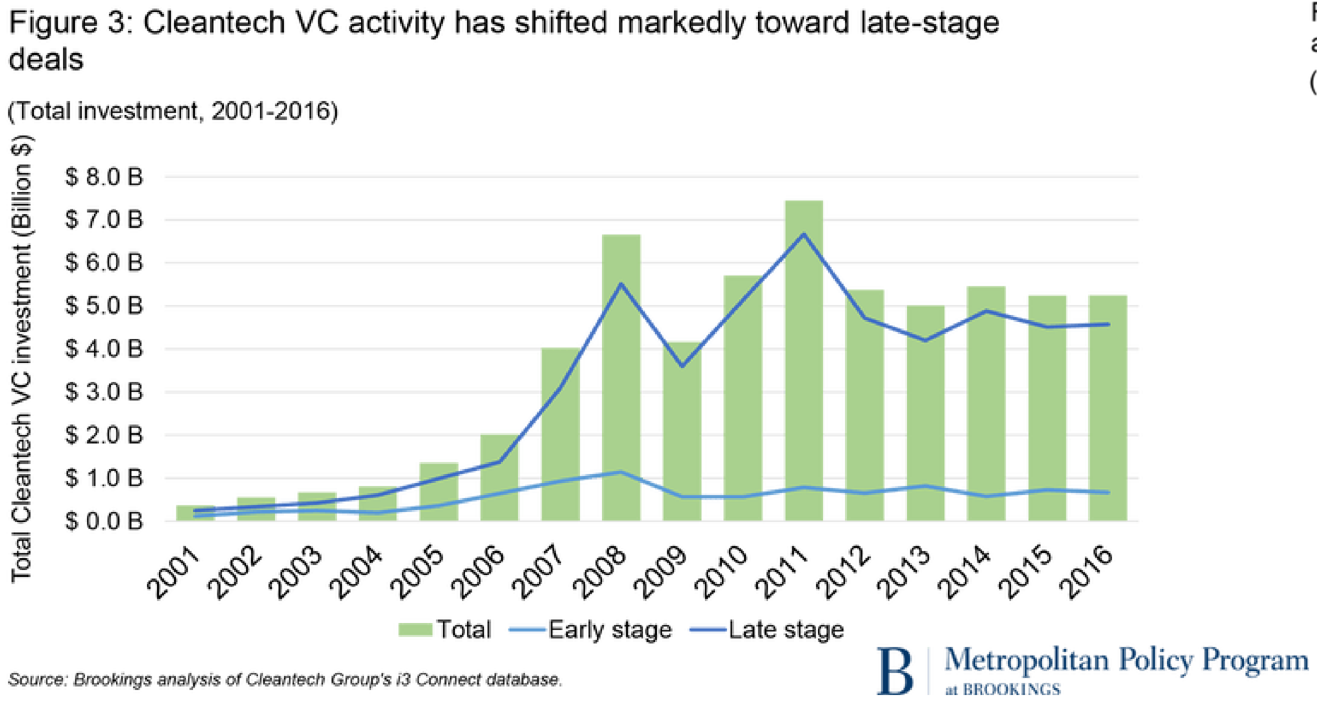
What’s limiting EGS?

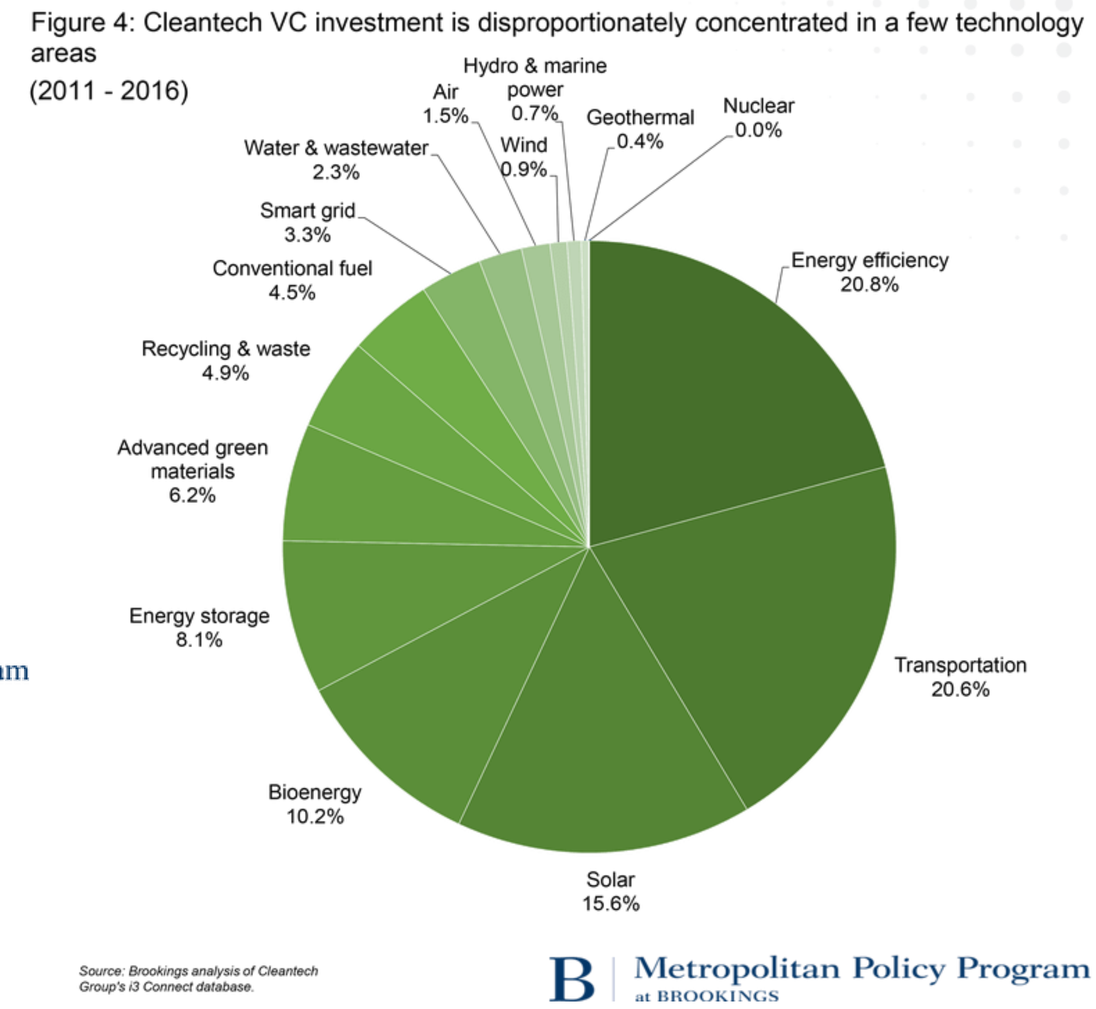
Drilling and exploration costs scale with the prize



GETEM Spreadsheet, GTO, 2017
Assumptions: 300° C resource, 30 MW plant, 25 year lifetime.

Minimal VC funding going toward geothermal





Total VC in any kind of geothermal: ~$21M/year

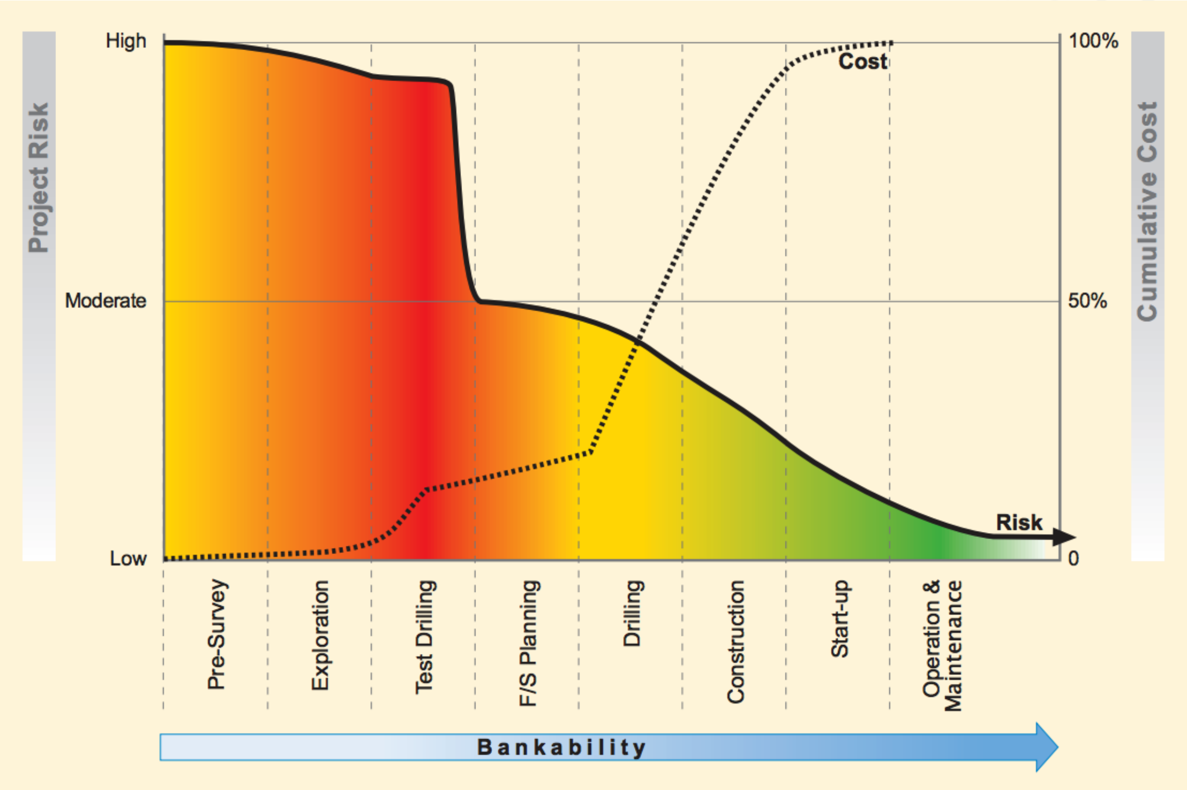
ARPA-E vision

ARPA-E vision: spark “unconventionals” revolution in geothermal

- De-risk radical new tools that could enable EGS development

Areas of interest:

1. High-resolution, low-cost surveying tools
2. HPHT downhole electronics/sensors
3. Precision reservoir designs
4. Radical reductions in drilling cost



Source | Authors.

ARPA-E vision: spark “unconventionals” revolution in geothermal

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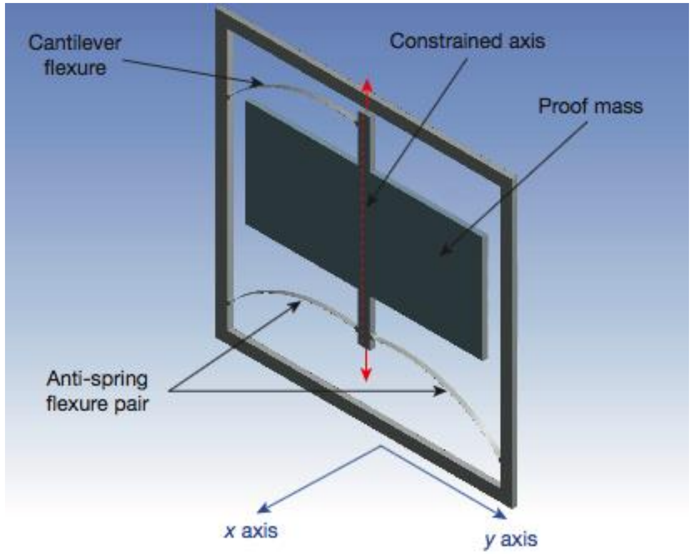
Narrow down and set priorities through this workshop

High-resolution, low-cost surveying tools

- What opportunities are there to improve cost and resolution in geothermal surveying tools?
  - Surface-based
  - Remote (e.g. from cube satellites)

SoA:

- ~1 µgal Hz$^{-1/2}$ sensitivity
- 8-150 kg
- ~Liter volumes
- ≥ $100k



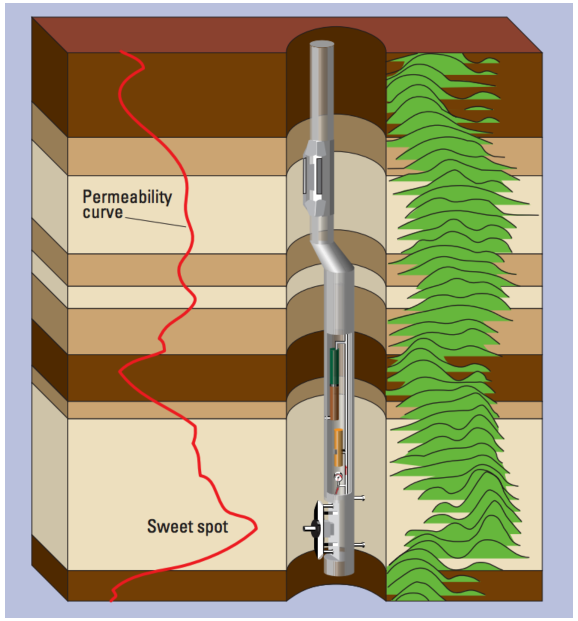
On-chip MEMS gravimeter

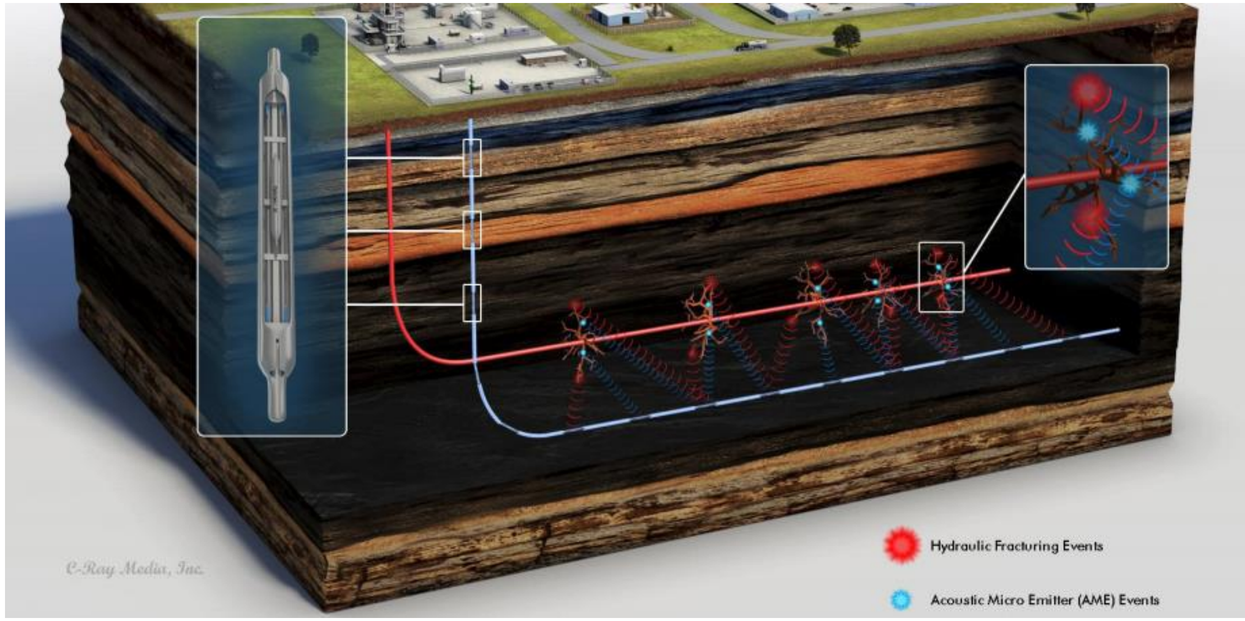
- 40 µgal Hz$^{-1/2}$
- ~gram masses
- ~cm^3 volumes

Middlemiss et al., *Nature*, **2016**, *531*, 614-617.

HPHT downhole electronics and sensors

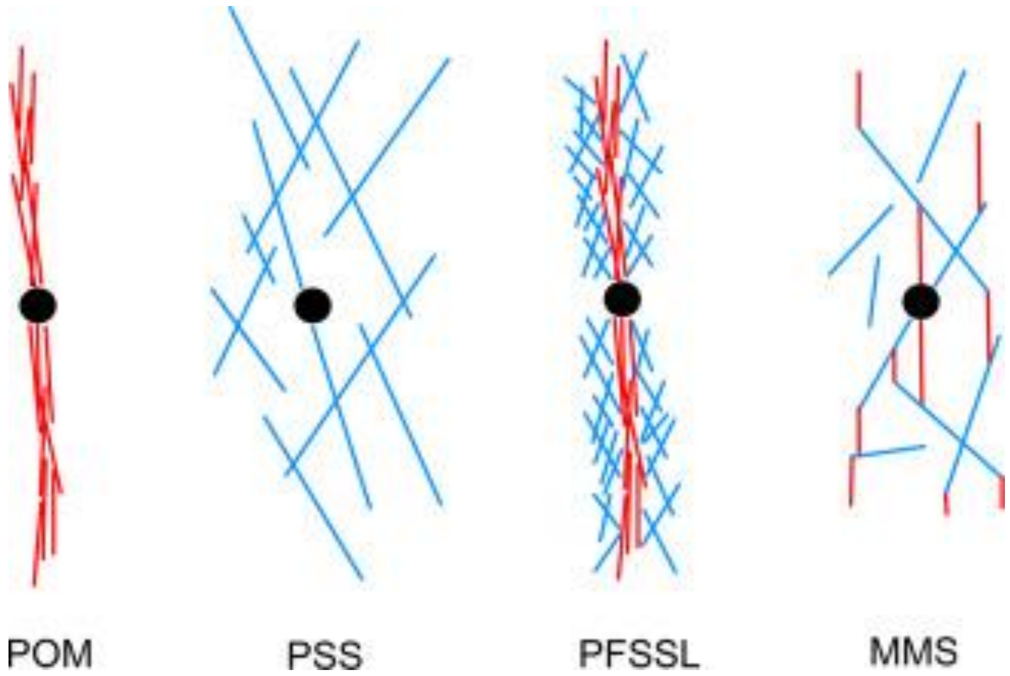
- Directional drilling requires computation in the bottom-hole assembly (BHA)
- Downhole sensors, processors, transistors, capacitors, etc. are needed
- How much of a challenge is communication back to surface?





New reservoir designs

- What does the ideal underground heat exchanger look like?
- How do you create and manage it?
  - Horizontal drilling
  - Directional fracking
  - Mixed-mechanism stimulation
  - Maintenance during decline
  - What would it take to produce from the brittle-ductile transition zone?



Traditional oil & gas framework

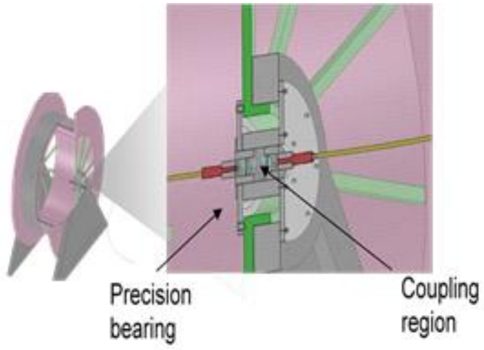
Traditional geothermal framework

Norbeck, McClure, and Horne, *Geothermics*, **2018**, *74*, 135-149.

Radical reductions in drilling cost

- Deeper (3-10 km), harder (granite), and hotter (>175 °C) than most O&G drilling
- Large cost; larger with greater depth

- SoA: 125 ft/day
- GTO goal: 250 ft/day
- Oil & gas capable of 1 mile/day



Foro Energy
OPEN 2009 awardee

Areas not of interest for this roundtable

- Incremental advances
- Test beds
- Models without a physical tool
- Improvements to practice
- Shallow (< 3 km) or low-temperature (< 250 °C) geothermal
- Main uses other than heat-to-electrons
  - Direct use, mineral co-production, storage
  - *these are OK as side benefits

Agenda

Time	Event
8:30 – 9:00 AM	**Registration**
9:00 – 9:15 AM	**Welcome and Introduction to ARPA-E** *Jennifer Gerbi, Associate Director for Technology, ARPA-E*
9:15 – 9:30 AM	**Roundtable Overview, Structure and Desired Outcome** *Isik Kizilyalli, Program Director, ARPA-E*
9:30 – 9:40 AM	**Attendee Introductions**
9:40 – 10:00 AM	**GTO Overview and Perspectives on EGS** *Sean Porse, DOE Geothermal Technologies Office*
10:00 – 10:20 AM	**EGS Cost and Performance Metrics** *Chad Augustine, NREL*
10:20 – 10:25 AM	**Breakout 1 Overview and Objectives** *Michael Campos and Lakshana Huddar, Fellows, ARPA-E*
10:25 – 11:00 AM	**Coffee break/Networking**
11:00 – 12:30 PM	**Breakout Session 1**
12:30 – 1:30 PM	**Lunch**
1:30 – 1:50 PM	**Modeling and Characterization of Fracture Roughness and its Impact on Heat and Mass Transport Processes** *Roland Horne, Stanford University*
1:50 – 2:10 PM	**Super Hot EGS: Reducing the Cost of Geothermal Through Technology Breakthrough** *Susan Petty, AltaRock Energy*
2:10 – 2:30 PM	**Overview of modern well-logging technologies and applications** *Yiqiao Song, Schlumberger-Doll Research Center*
2:30 – 2:35 PM	**Breakout 2 Overview and Objectives** *Michael Campos and Lakshana Huddar, Fellows, ARPA-E*
2:35 – 2:40 PM	**Networking/Transition to Breakout Session 2**
2:40 – 3:50 PM	**Breakout Session 2**
3:50 – 4:00 PM	**Wrap-up/open discussion**
4:00 – 6:00 PM	**One-on-one meetings (optional)**

Breakout Session Structure

- SESSION 1: Instrumentation
  - High-temperature downhole electronics
  - Remote sensing tools
- SESSION 2: Precision reservoir design
  - Controlled fracture techniques
  - Using AI/ML for precision drilling

- Questions that permeate both sessions:
  - Are there opportunities to leverage O&G knowledge base and infrastructure?
  - What size projects would be needed? $100k? $1M? $10M?

Guidelines for the day

- Think big!
- We need your input!
- Poke holes in ideas – no need to come to consensus
- Make sure we're not missing anything
- Please don't discuss any ongoing OPEN proposals
- It's possible there's no program here

- Several one-on-one meeting slots are still available – see Laura Demetrion

Questions?

EGS investment is less attractive than oil & gas

Factor	Oil & Gas	EGS
Geology	• Soft sedimentary rock • Stable, regular formations • Straightforward seismic surveying	• Hard basement rock • Fractured formations, often volcanic • Difficult seismic surveying
Fluid composition	• < 175 °C • Variation by field, maturity	• 200+° C desirable • Variation by field, some steam unusable for power generation
Reservoir lifetime	• 1-5 years for unconventionals	• 25-30 years
Economy/markets	• Internationally traded • Easy to store, transport, and sell	• Feeds into local grid • Limited selling options • Additional infrastructure and contracts needed

Geothermal Handbook: Planning and Financing Power Generation, ESMAP, 2012.